Dynamical Freeze-Out vs. Chemical Equilibrium at SPS and RHIC

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- first order phase transition in a combined macro/micro approach
- reaction dynamics, flow and freeze-out of multi-strange baryons
- implications of radial flow on freeze-out
- critical interpretation of Statistical Model fits to yields/ratios

Time-Evolution of a Relativistic Heavy-Ion Collision

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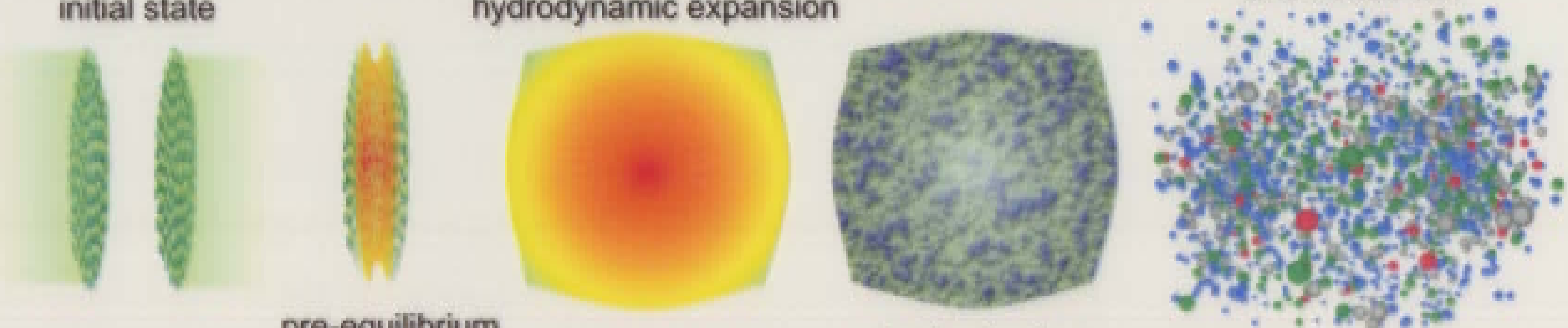

Experiments: observe ashes of deconfined state (hadrons, leptons)

⟶ rely on *signatures* predicted by theory

Transport-Theory: full description of collision dynamics

(from initial state to freeze-out)

⟶ connects deconfined state to experimental observables

A combined macro/micro transport model

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Hydrodynamics

- ideally suited for dense systems
→ model early QGP reaction stage
- well defined Equation of State
→ incorporate 1st order p.t.
- parameters:
  - initial conditions
  - Equation of State

micro transport (UrQMD)

- no equilibrium assumptions
→ model break-up stage
→ calculate freeze-out
- parameters:
  - (total/partial) cross sections
  - resonance parameters (full/partial widths)

matching conditions:

- use same set of hadronic states for EoS and UrQMD
- generate space-time distribution of hadrons at end of mixed phase (hadronization hypersurface)
→ use as initial configuration for UrQMD

Scaling Hydrodynamics

$$\partial_\mu T^{\mu\nu} = 0 \quad , \qquad \partial_\mu j_i^\mu = 0$$

for ideal fluid:

$$T^{\mu\nu} = (\epsilon + p)u^\mu u^\nu - p g^{\mu\nu}$$

$$j_i^\mu = \rho_i u^\mu$$

assumptions: longitudinal boost-invariance

cylindrically sym. transverse expansion

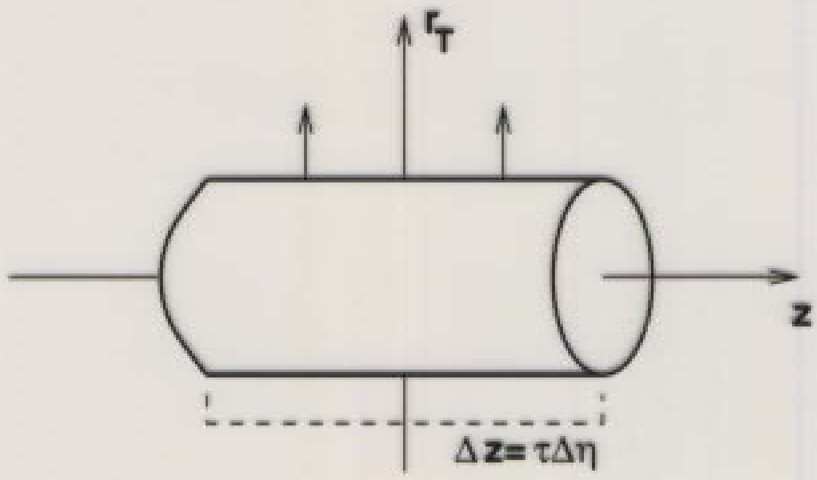
$$u^\mu(x^\mu) = \gamma_\perp\,(\cosh\eta,\, v_\perp \sin\phi,\, v_\perp \cos\phi,\, \sinh\eta)$$

with $\tanh\eta \equiv v_\parallel = z/t$

$\frac{\partial p}{\partial \eta}|_\tau = 0$ no pressure between rapidity "slices"

$\frac{\partial R_i}{\partial \eta}|_\tau = 0$ conserved charge in each "slice",

$R_i = \int \mathrm{d}^2 r_\perp\, \rho_i(\vec{r_\perp})$



Scaling Hydrodynamics: EoS

Hadronic Phase

ideal hadron-gas including all (strange + non-strange) states up to $m \approx 2$ GeV (including resonances)

$$\text{with} \quad p = \sum_i \int \frac{\mathrm{d}^3 p}{p^0} \vec{p}^2 f_i$$

$$\text{and} \quad s = \frac{\partial p(T, \mu_i)}{\partial T}, \quad \rho_i = \frac{\partial p(T, \mu_i)}{\partial \mu_i}$$

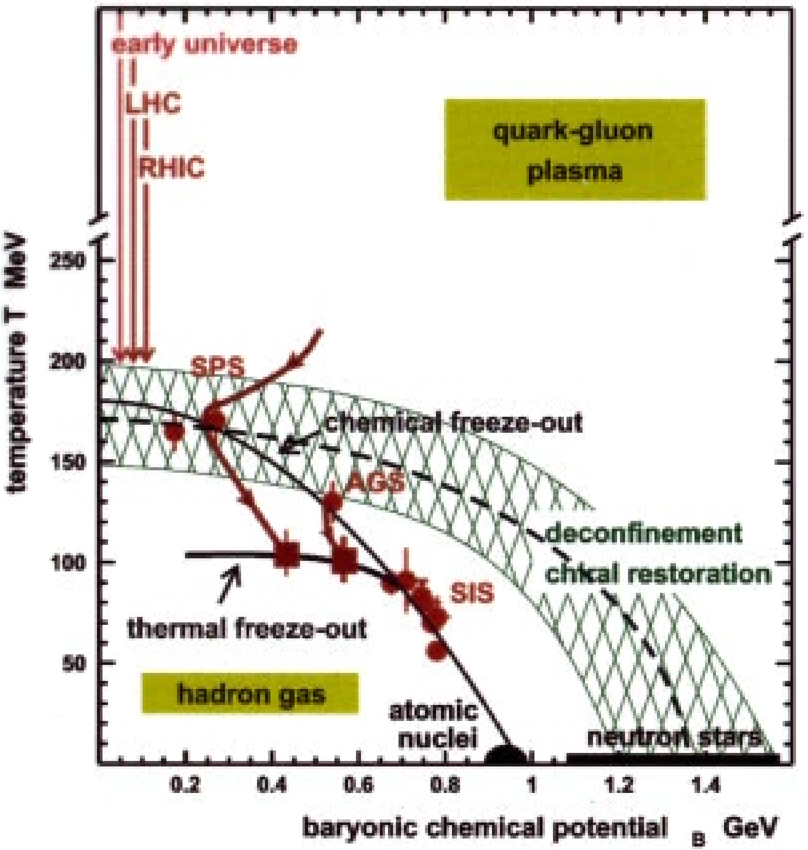
QGP Phase

MIT bag-model EoS for ideal QGP ($\alpha_s = 0$) of u, d and s quarks and gluons with $m_s = 150$ MeV, $m_u = m_d = 0$ MeV and $B = 380$ MeV/fm^3
$\Rightarrow T_C(\rho_B = \rho_S = 0) = 162$ MeV

Mixed Phase

$$p^{QGP}(T, \mu_i) = p^{HG}(T, \mu_i)$$

Critical Interpretation of Statistical Model Fits

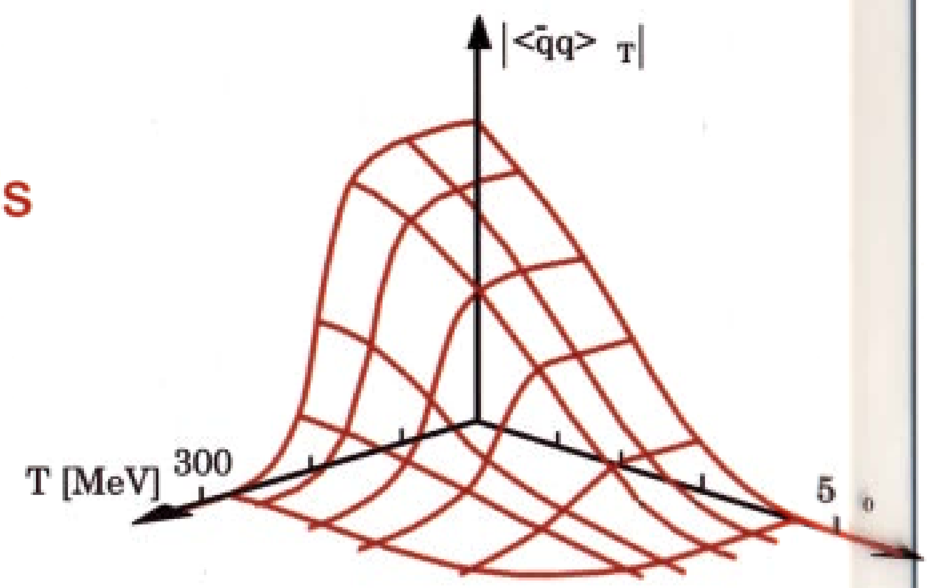


- Statistical Model fits to hadron yields/ratios seem to work well
- Common interpretation: chemical freeze-out close to phase-boundary with T T_C

» However: hadron masses change properties close to T_C!

» SM fit with on-shell masses is inconsistent with physics of fit-results!

» Need to employ model that takes proper physics at T_C into account



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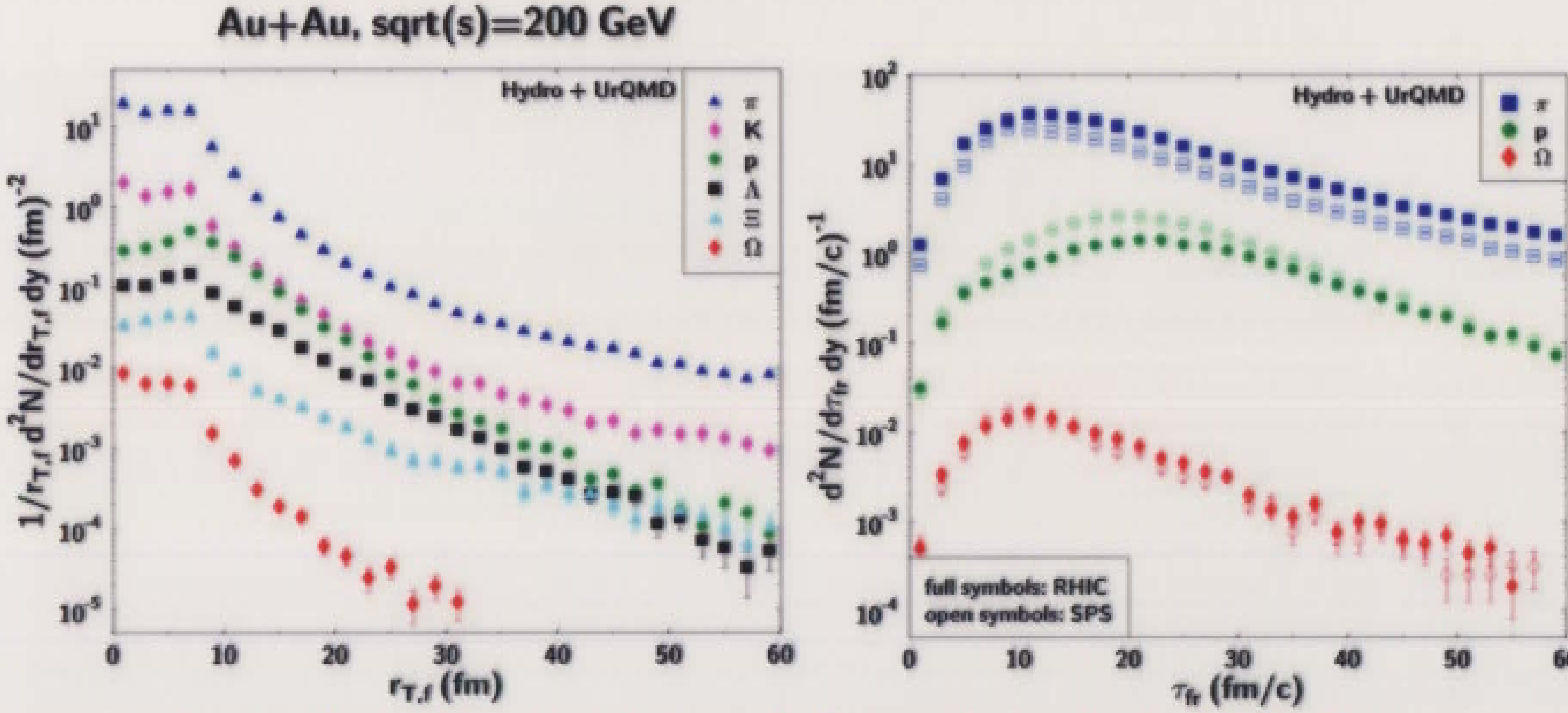
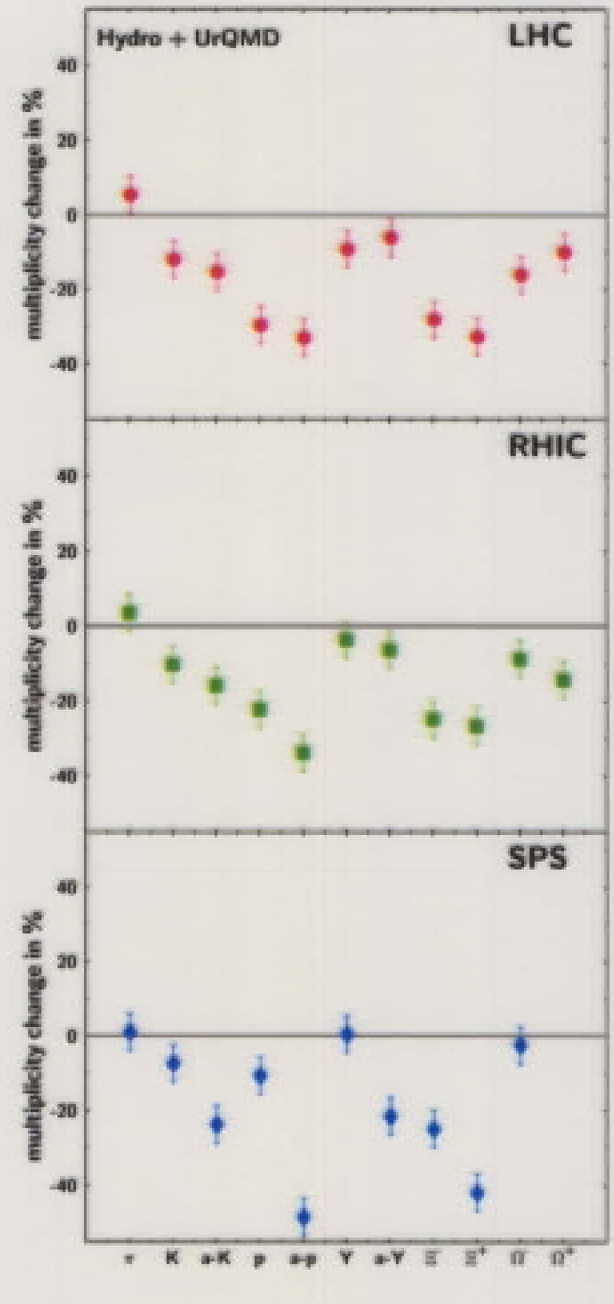
Freeze-Out: Flavor Dependence



- no sharp freeze-out: broad, flavor-dependent distributions
- only very small difference in lifetime from SPS to RHIC
  - use HBT as tool to investigate freeze-out behavior

Chemistry of the Hadronic Phase: Rescattering and Particle Yields



- rescattering changes yields up to 40 %

⇒ no chemical freeze-out at phase-boundary

Mass-dependence of m_T-slope parameters

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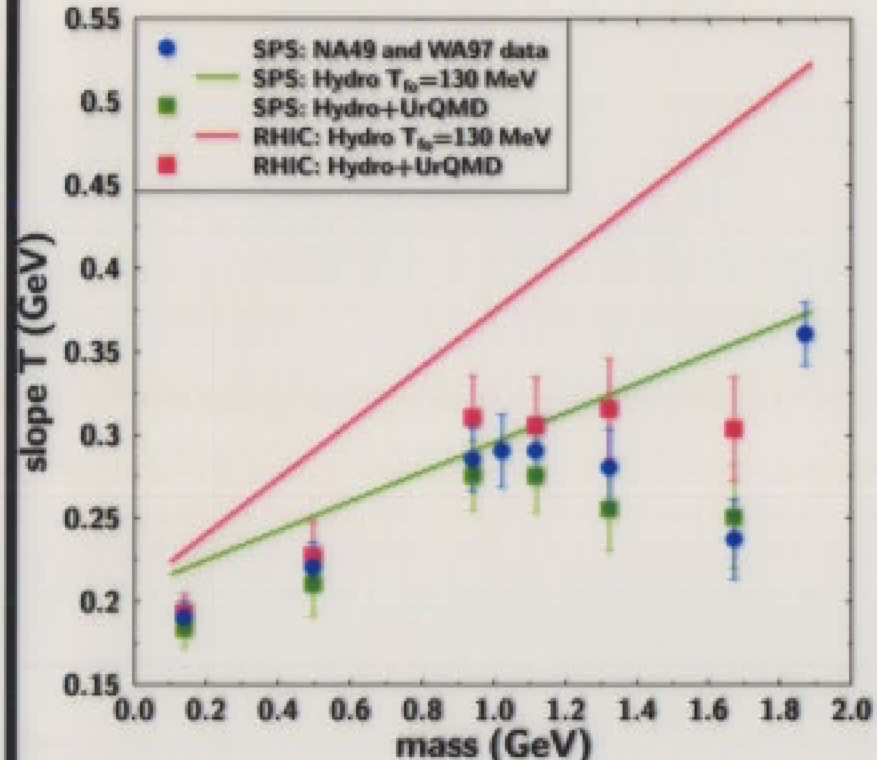

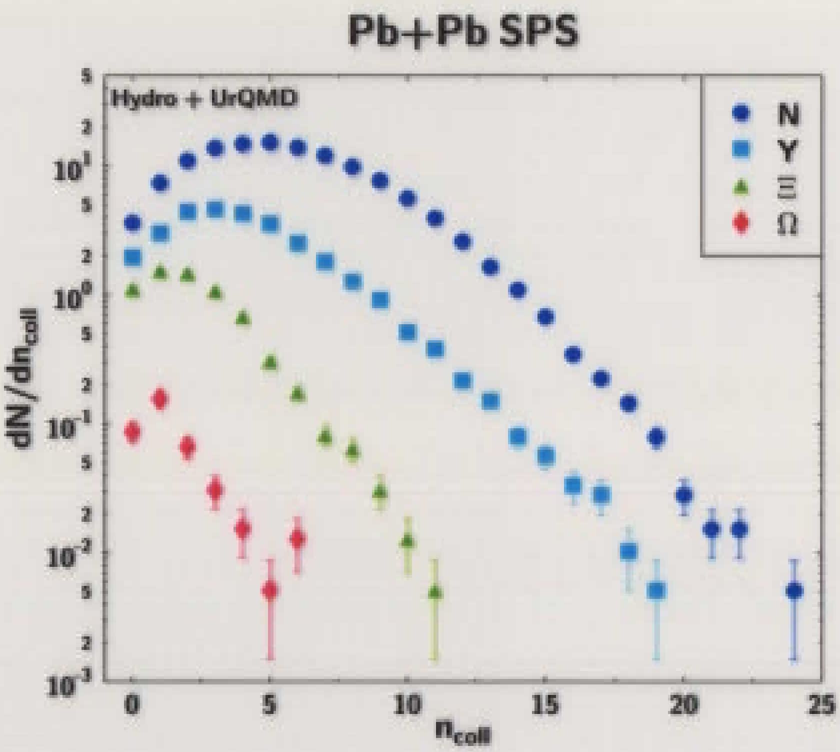

- Hydro: linear mass-dependence of slope parameter, strong radial flow
- Hydro+Micro: softening of slopes for multistrange baryons

→ early decoupling due to low collision rates

⇒ nearly direct emission from the phase boundary

- RHIC: FO occurs closer to hadronization hypersurface than at SPS

Rescattering of multi-strange baryons

- inelastic scattering, predominantly via MB-resonance states: $\Xi^*_{1530}, \Xi^*_{1690}, \Xi^*_{1820}, \Xi^*_{1950}, \Xi^*_{2030}$
  possible decay channels: $\Xi^* \rightarrow \Xi\pi, \Xi\gamma, \Lambda\bar{K}, \Sigma\bar{K}$

- $\pi\Omega$ resonant states?

$\rightarrow$ quantum numbers allow only isoscalar $(\pi^0\Omega^-)$ state, however coupling (Clebsch-Gordan) is zero!

- resonance continuum with $m_R > 2.5$ GeV: implemented via string-excitation
  for $\Omega + h \rightarrow \textit{string}$: $\Delta E_{th} \approx 1$ GeV needed

$\rightarrow$ not likely in hadronizing QG-fluid with common flow velocity

- elastic scattering:
  $m_{\Omega,\Xi} \gg m_\pi$: negligable effect on $\vec{p}_{\Omega,\Xi}$ and $\vec{v}_{\Omega,\Xi}$
  $\Rightarrow$ no influence on m_T-spectra

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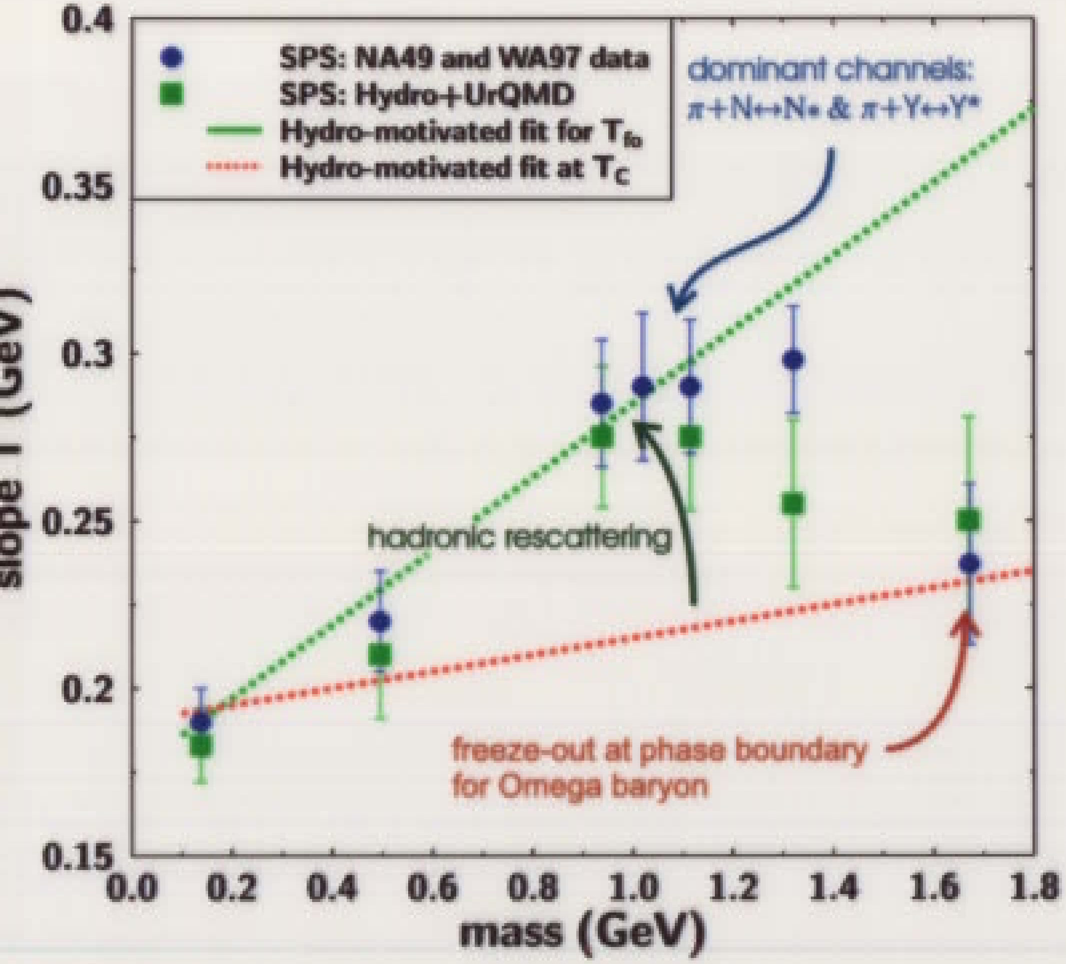
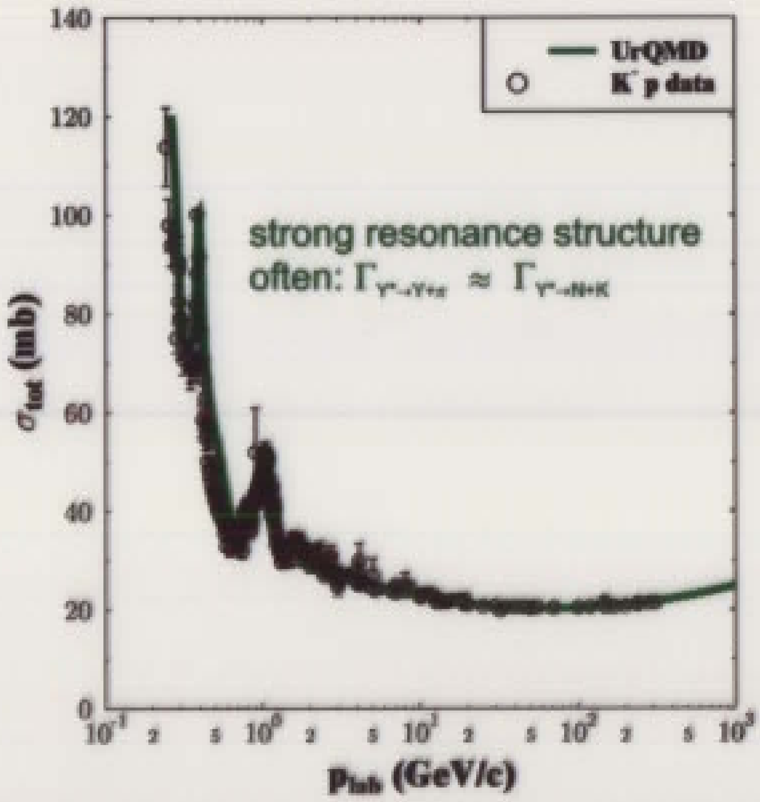
Radial Flow: Implications on Chemical Freeze-out



- strong evidence for sequential decoupling of system in the hadronic phase
- kinetic/thermal freeze-out is flavor dependent
- chemical freeze-out at phase boundary implies:
  » quasi-elast. rescattering for all flavors



→hyperon meson rescattering may change flavor chemistry

→ chemical freeze-out at phase-boundary is questionable

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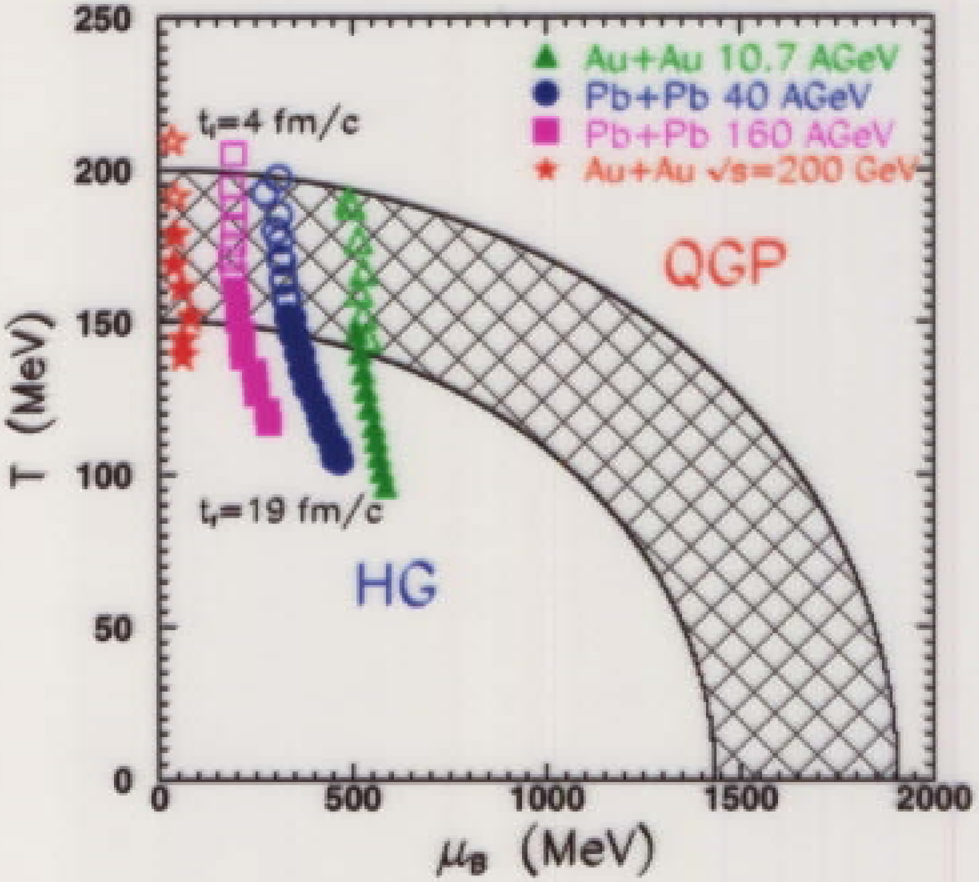
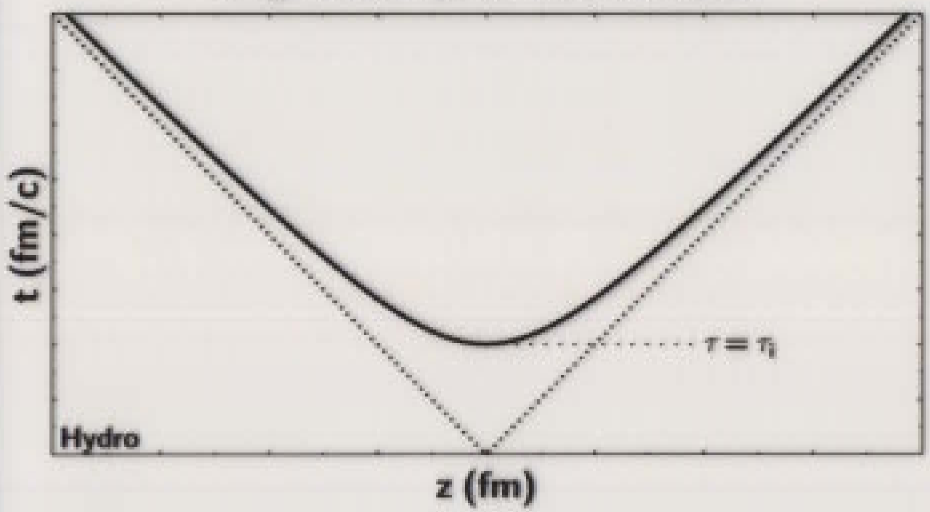
Hadron yields and ratios in a dynamical scenario

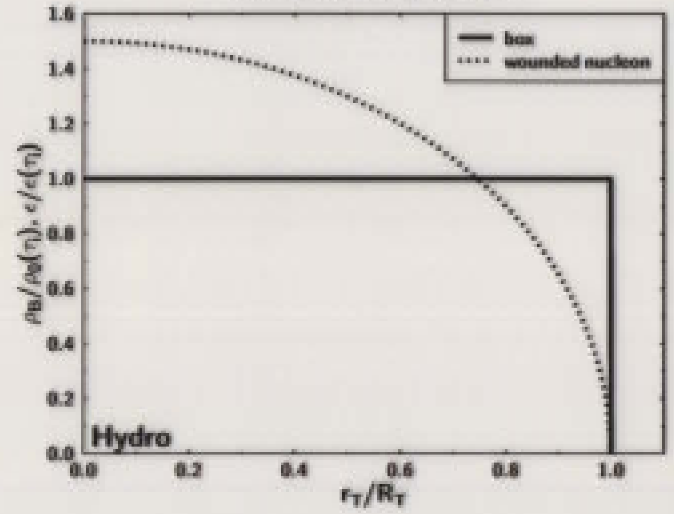


- sytem evolves through a continuous series of equilibrated states
- decoupling of individual hadron species takes place sequentially during that evolution

→ final state is superposition of particles emitted at different T and μ_B

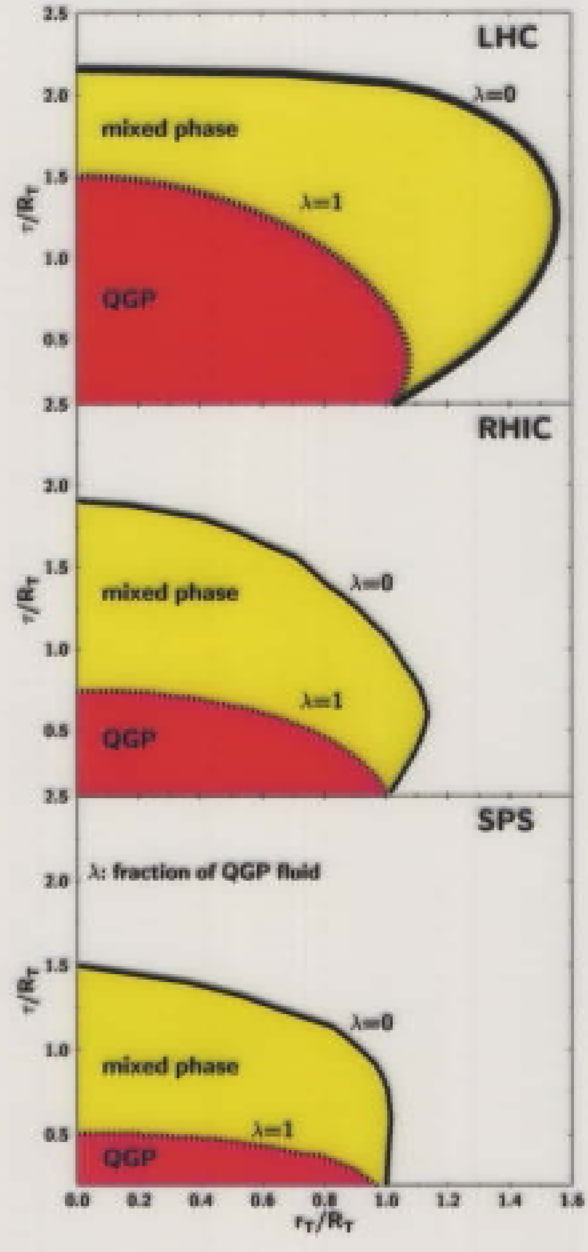
Scaling Hydrodynamics: Initial Conditions





SPS	RHIC
$\frac{dN_B}{dy} = 80$, $\frac{\bar{s}}{\rho_B} = 45 \pm 5$, $\tau_i = 1$ fm/c	$\frac{dN_B}{dy} = 25$, $\frac{\bar{s}}{\rho_B} = 205$, $\tau_i = 0.6$ fm/c
$\bar{\epsilon}(\tau_i) = 6$ GeV/fm^3, $T = 220$ MeV	$\bar{\epsilon}(\tau_i) = 20$ GeV/fm^3, $T = 300$ MeV
$\frac{dE_\perp}{dy}$: 600 GeV (τ_i) $\rightarrow$ 457 GeV (fo)	$\frac{dE_\perp}{dy}$: 1.3 TeV (τ_i) $\rightarrow$ 714 GeV (fo)

Hydrodynamic Space-Time Evolution



- evolution starts with QGP from $r_T = 0$ to $r_T = R_T$
- initial cooling through longitudinal expansion
- large transverse pressure gradients at surface

⇒ creation of strong transverse flow

Scaling Hydrodynamics: Particle Distributions

The transition to microscopic dynamics requires full space-time- and momentum coordinates for each hadron at hadronization:

$$\frac{\mathrm{d}N_i}{m_\perp \mathrm{d}m_\perp \mathrm{d}y\, \mathrm{d}\eta\, \mathrm{d}\xi\, \mathrm{d}\phi} = r_\perp \tau \left(p_\perp \cos\phi \frac{\mathrm{d}\tau}{\mathrm{d}\xi} - m_\perp \cosh(y-\eta) \frac{\mathrm{d}r_\perp}{\mathrm{d}\xi} \right) f_i(p{\cdot}u)$$

with: four momentum $p^\mu = (m_\perp \cosh y, p_\perp sin\chi, p_\perp \cos\chi, \sinh y)$

fluid 4-velocity $u^\mu = \gamma_\perp (\cosh\eta, v_\perp \sin\phi, v_\perp \cos\phi, \sinh\eta)$

and χ angle between $\vec{p}_\perp$ and transverse plane

ϕ relative angle between $\vec{p}_\perp$ and $\vec{v}_\perp$ (transverse flow velocity)

- $r_\perp(\xi)$ and $\tau(\xi)$ with $\xi \in [0,1]$ parameterize space-time points of the hadronization hypersurface

$\Rightarrow$ assume $v_\perp, T$ and μ independent of η:
hypersurface is proper-time hyperbola in $t-z$ plane (at fixed $r_\perp$)

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The UrQMD model

- elementary degrees of freedom: hadrons, const. (di)quarks
- classical trajectories in phase-space (relat. kinematics)
- initial high energy phase of the reaction is modelled via the excitation and fragmentation of strings
- UrQMD contains 55 baryon- and 32 meson-species, among those are 25 N^*, Δ^* resonances and 29 hyperon/hyperonresonance species

⇒ ideal for the description of excited hadronic matter

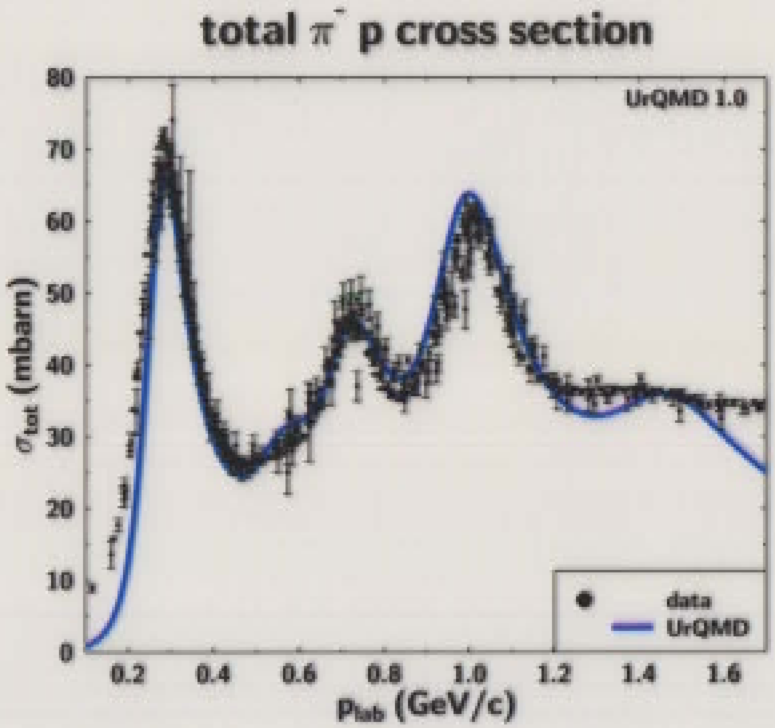
- an interaction takes place if at the time of closest approach d_{min} of two hadrons the following condition is fulfilled:

$$d_{min} = \sqrt{\frac{\sigma_{tot}}{\pi}} \quad , \sigma_{tot} = \sigma_{tot}(\sqrt{s}, |h_1\rangle, |h_2\rangle)$$

- full baryon-antibaryon and isospin symmetry concerning hadronspecies and interactions

Process	Parameter
elast. scatt.	σ_{part}, $\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}$
inelast. scatt.	σ_{part}, $\Gamma(M)_{tot}$, $\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}$, detailed balance
resonance-decay	$\Gamma(M)_{part}$, $\tau(\Gamma_{tot})$
string-excitation	σ_{part}, fragmentation-functions, formation probabilities

Meson Baryon Cross Section

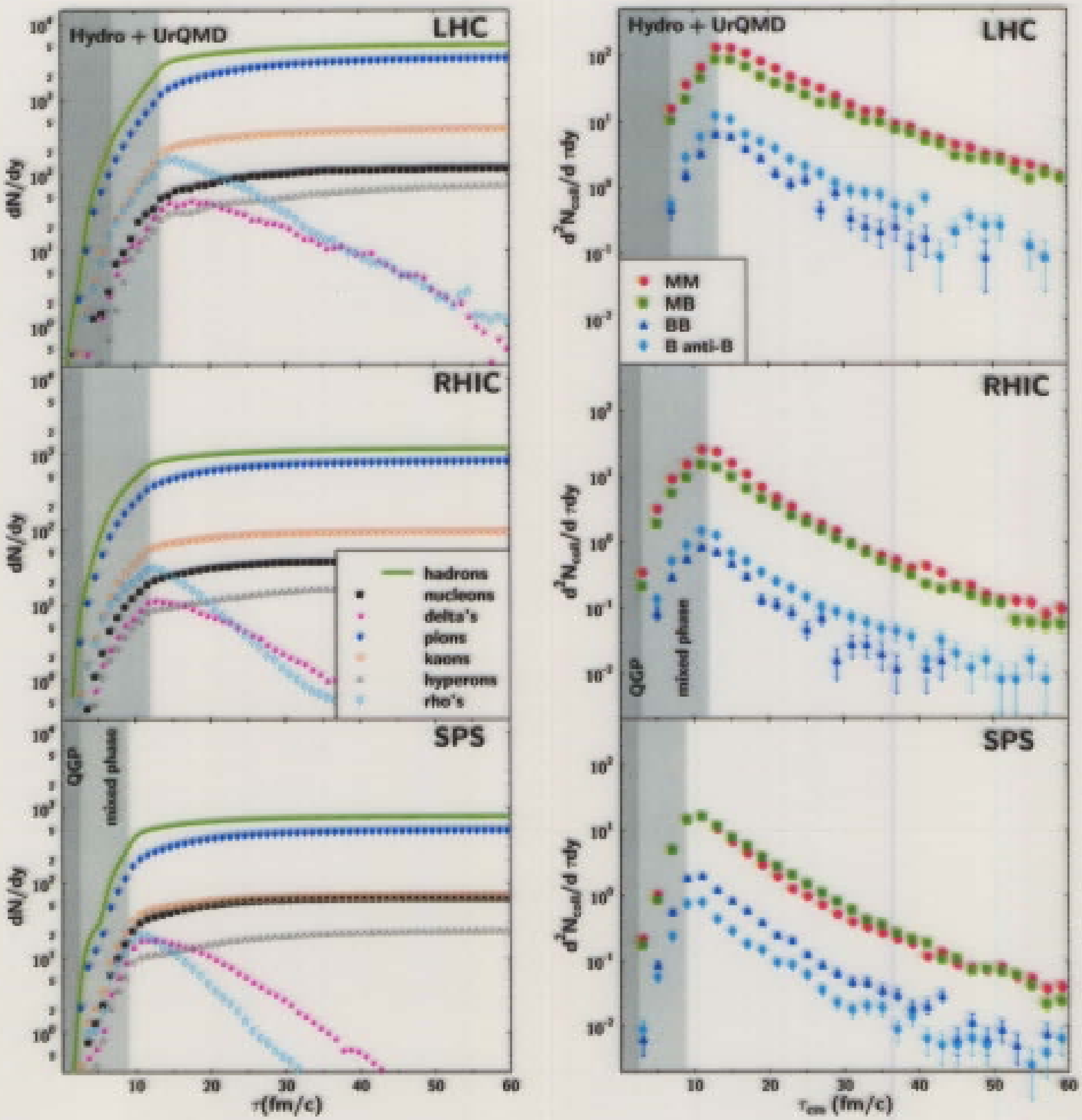


Δ^*	width	N^*	width
Δ_{1232}	120 MeV	N^*_{1440}	200 MeV
Δ_{1600}	350 MeV	N^*_{1520}	125 MeV
Δ_{1620}	150 MeV	N^*_{1535}	150 MeV
Δ_{1700}	300 MeV	N^*_{1650}	150 MeV
Δ_{1900}	200 MeV	N^*_{1675}	150 MeV
Δ_{1905}	350 MeV	N^*_{1680}	130 MeV
Δ_{1910}	250 MeV	N^*_{1700}	100 MeV
Δ_{1920}	200 MeV	N^*_{1710}	110 MeV
Δ_{1930}	350 MeV	N^*_{1720}	200 MeV
Δ_{1950}	300 MeV	N^*_{1990}	300 MeV

→ calculate cross section according to:

$$\sigma_{tot}^{MB} = \sum_{R=\Delta,N^*} \frac{2I_R+1}{(2I_B+1)(2I_M+1)} \frac{\pi}{p_{CMS}^2} \frac{\Gamma_{R\to MB}\Gamma_{tot}}{(M_R-\sqrt{s})^2+\frac{\Gamma_{tot}^2}{4}}$$

Multiplicities and Collision Rates



- long lifetime of mixed and hadronic phase
- rescattering dominated by MM and MB
- chemical freeze-out influenced by hadronic phase